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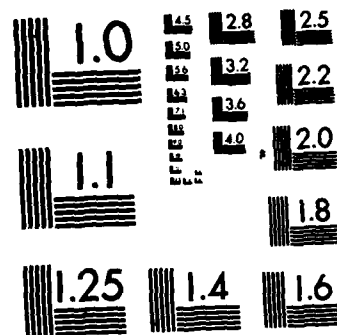
COSMIC RAY ACCESS TO SATELLITES FROM LARGE ZENITH  
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## COSMIC RAY ACCESS TO SATELLITES FROM LARGE ZENITH ANGLES

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## ABSTRACT

As the altitude of earth-orbiting satellites increases it becomes progressively easier for primary cosmic-ray particles to gain access to them from directions below the geometric horizon. Results are presented from a comprehensive survey of the largest accessible zenith angles for a range of altitudes and geographic locations. The search has disclosed that primary particles are able to reach a satellite at an altitude of 1250 km from zenith angles as large as  $178^\circ$ .

## 1. Introduction

Some interest has been expressed in recent times in the ability of primary cosmic-ray particles to reach satellites in low altitude earth-orbit from directions below the local horizon. At the Paris Cosmic Ray Conference, Humble et al. (1981) showed that primary particles are able to reach a satellite at a zenith angle of  $120^\circ$  from a range of western azimuths at all the geographic locations which were investigated. The calculations were substantiated by the results of experiments on board the HEAO-C satellite (N.Lund, private communication 1981). The investigation reported here extends these studies by determining in a systematic fashion the largest zenith angles accessible to primary particles at a selected range of azimuths and set of satellite altitudes and locations.

Calculations are reported for altitudes of 400, 800 and 1250 km, for latitudes at  $20^\circ$  intervals from  $40^\circ\text{N}$  to  $40^\circ\text{S}$  at each altitude, and longitudes at  $60^\circ$  intervals starting at  $0^\circ$  at each latitude. For each location thus defined a suitable range of azimuths likely to be accessible to primary particles at zenith angles of  $120^\circ$  or larger (Humble et al., 1981) was investigated.

## 2. Method

The calculations have been carried out using the standard trajectory calculation program (Shea et al., 1965). For continuity with earlier work we have continued using the former International Geomagnetic Reference Field for 1980.0, as extrapolated from IGRF 1975.0 with the use of

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secular correction coefficients (IAGA Study Group, 1976). We note that future calculations should use the new definitive ICRF 1980.0 model resulting from the Edinburgh meeting of IAGA (Peddie, 1982).

As zenith angles increase at a particular location and azimuth of arrival the Horizon Limited Rigidity\* necessarily decreases, due to the increased curvature required for the final stage of the trajectory (Humble et al., 1981). A similar situation holds true for particular penumbral bands. The rather simple minded, but effective, search technique used was, therefore, to commence calculations at zenith angle  $120^\circ$  and a large rigidity, usually around 30 GV. If this trajectory was allowed the zenith angle was incremented by  $2^\circ$  whilst if it was forbidden the rigidity was decremented by 1%. The process was then repeated at the new zenith or rigidity.

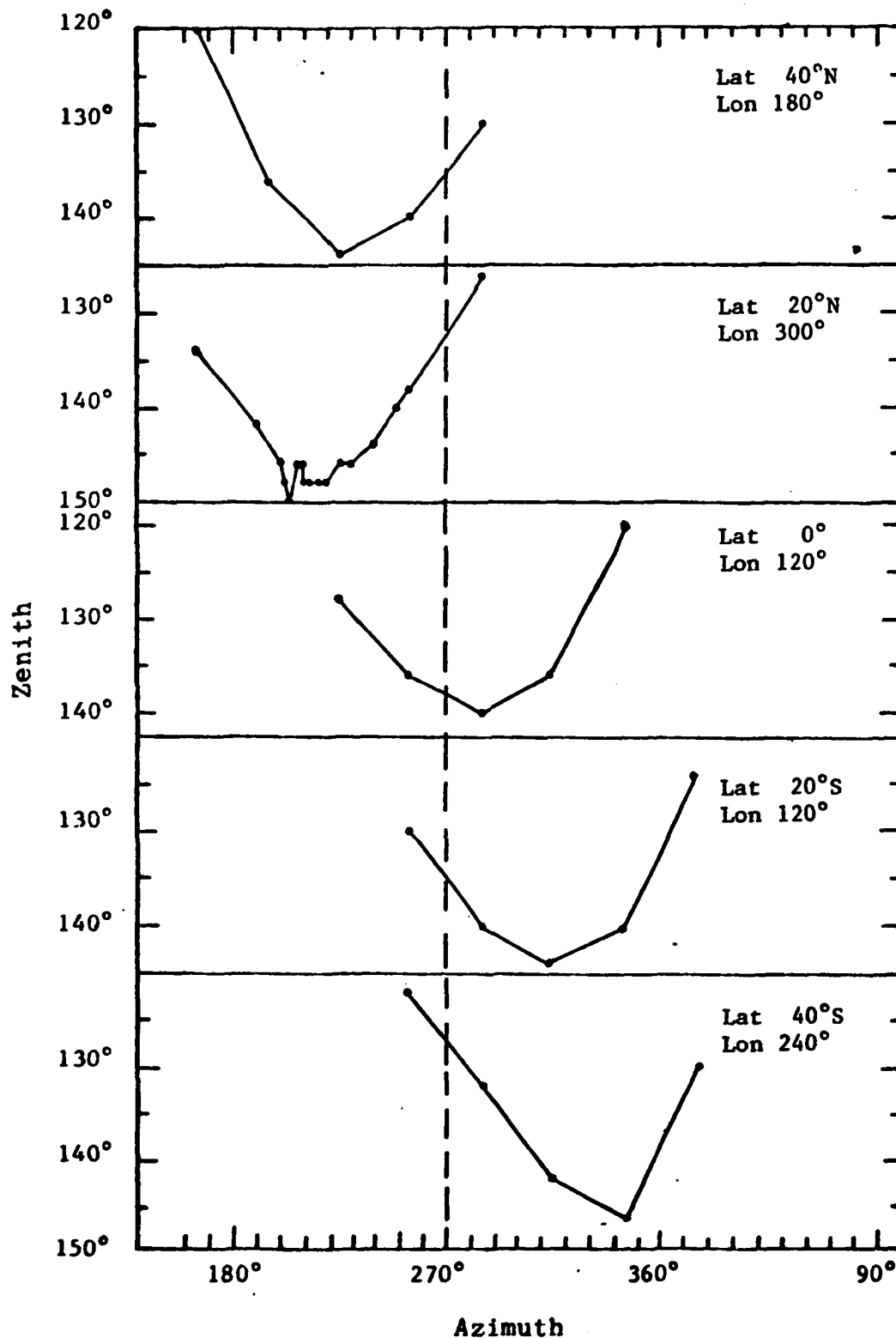
The technique is fast, in that the majority of the trajectories involved are simple ones. It has the effect of following particular penumbral features through increasing zenith angles. If one such band ends as zenith angle increases the next lowest (in rigidity space) band is automatically found. This process continues until the Störmer cone is encountered. The technique does ignore the possibility that a penumbral allowed band may exist at relatively high rigidities extending to larger zenith angles than do the lower rigidity bands first explored. One or two such examples have been found, the clear implication being that great care must be used in selecting the starting rigidity.

### 3. Results and Discussion

The largest accessible zenith angles,  $Z$ , found at each location are listed below.

Altitude	Longitude	0	60	120	180	240	300
400 km	40 N	144	142	142	144	138	136
	20 N	140	140	138	136	144	148
	0	138	138	140	138	138	138
	20 S	136	142	144	144	136	136
	40 S	136	136	130	138	146	140
800 km	40 N	156	154	156	156	148	146
	20 N	164	160	160	160	164	162
	0	158	160	160	160	158	162
	20 S	156	156	158	166	160	156
	40 S	146	146	140	148	158	158
1250 km	40 N	162	162	162	162	156	152
	20 N	178	178	176	178	172	168
	0	172	174	174	176	176	178
	20 S	166	164	166	174	174	170
	40 S	154	154	148	154	164	170

\*The highest rigidity with which primary particles can reach the site. This was called "Allowed Rigidity" in our 1981 paper; we believe the present name to be more descriptive.



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Figure 1 shows scans of the largest accessible zenith angles found versus azimuth, for one site at each latitude at 400 km altitude. Note that the largest zenith angle accessible at each site occurs at azimuths to the equatorward of West. This is true in all cases which we have investigated. Note also the fine details plotted for  $20^{\circ}\text{N}$   $300^{\circ}$ . Extensive calculations were undertaken at this site.

The distribution of  $Z$  with latitude varies according to the altitude involved. At 400 km there is no detectable relationship between  $Z$  and latitude. However, a relationship begins to be apparent at 800 km, and is much more obvious at 1250 km, at which altitude the largest values of  $Z$  are found between  $20^{\circ}\text{N}$  and  $20^{\circ}\text{S}$ . The  $Z$  values at higher latitudes are noticeably reduced.

The largest values of  $Z$  found at each altitude, and indicated in the table, are  $148^{\circ}$  at 400 km,  $166^{\circ}$  at 800 km, and  $178^{\circ}$  at 1250 km. These compare with horizon zenith angles of  $110^{\circ}$ ,  $117^{\circ}$ , and  $123^{\circ}$  respectively. The listings only indicate values actually found at a selected grid of locations. They do not exclude the possibility of larger values being found at non-grid locations. The limited spot checks which we have made at 400 km only, for various latitudes between  $40^{\circ}\text{N}$  and  $20^{\circ}\text{S}$  have revealed one such case, an allowed trajectory at a zenith angle of  $150^{\circ}$ . Due to the method used we cannot completely guarantee that larger angles than those listed also exist at the grid locations. However, we believe that significant variations are unlikely.

It should also be noted that the calculations are artificial in one important respect. They assume, along with earlier calculations, that all particles descending below a local altitude of 30 km undergo interaction with the atmosphere. The general agreement referred to earlier between the HEAO-C observations and early calculations for 400 km altitude suggest that the assumption may be reasonable, but the point requires elucidation.

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